Standardization Suggested by the AMRF - A Research Testbed for the Factory of the Future

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ABSTRACT: A research effort has been initiated at the National Bureau of Standards to develop a small batch manufacturing system to support study and experimentation in automated metrology and interface standards for the computer integrated factory of the future. When completed, the resulting testbed system will be made available for fundamental studies in manufacturing technology by scientists and engineers from government, industry, and universities. This paper will report on the progress of major software and hardware subprojects that are being carried out in support of the construction of the AMRF.

The basic approach to the research effort is to take the structure of an automated manufacturing facility and decompose the functional elements in a top-down fashion until the elements are no longer divisible. At this level, systems are defined for robots, machine tools, carts, conveyors, and other similar type units. The project will define the processes that occur at each level, how they can be measured using sensors with software support, and the interface specifications between modules.

Projects will address the applications of 1) hierarchical control techniques to implement the factory command structure, 2) artificial intelligence/expert systems, and decision support systems for work on distributed process planning and scheduling functions, 3) distributed data management systems to handle the problem of a wide spectrum of data requirements, and 4) network communications techniques to manage the various data flow requirement through all levels of the factory system.

Other projects will address the issue of software support systems for an automated system. Graphics interfaces for a manufacturing environment will be developed based on human engineering considerations. Simulation and emulation systems are and will continue to be used for the design and testing of automated systems.

Some projects will address the problem of making the elementary unit, such as robots, more capable of responding to a changing environment. These projects include adding many types of sensors - vision, tactile, force, proximity, etc. to the robot system to allow for a more sensory interactive real time control system. A continuing project utilizing sensors on machine tools has demonstrated the ability to improve a machine tool's accuracy. These projects will lead to adaptive control being performed at the equipment level.

I. Introduction

The National Bureau of Standards (NBS) is addressing the measurement and standards needs for the automation of the small batch, discrete parts manufacturing industries such as those supplying parts for aircraft, automobiles, and industrial machinery. These industries produce goods that account for 75 percent of all U.S. trade in manufactured goods. Although this sector of the U.S. economy includes 35 percent of all U.S. manufacturing firms, over 100,000 of these firms (or 87 percent of the total) have less than 50 employees. It now appears that these industries must automate to successfully compete, in both foreign and domestic markets, with Japan, Germany, and other industrial countries which have major government sponsored programs in automation.

The aspect of manufacturing that has been chosen for research is the completely automated small-batch manufacturing system, or flexible manufacturing system. It consists of such elements as metal cutting machines, computers, terminals, robots, conveyers, and measuring or inspection systems. Such a system produces a variety of shapes and sizes of parts and may assemble them into larger systems; for example, gears, shafts, and cases into transmissions.

The role of NBS in automated manufacturing is twofold: 1) to provide the basis for measurement assurance, a means by which the dimensional attributes of manufactured products can be traced to national standards; and 2) to assist in the development of those voluntary standards necessary for the successful automation of industry. Basic and exploratory research is carried out, as needed, to support these major functions.

An Automated Manufacturing Research Facility (AMRF) is being developed to serve as a major testbed and demonstration facility to support the automation research of NBS staff and researchers from industry, academia, and other government agencies. When it becomes fully operational in 1986, the AMRF will provide both a focus for research efforts and a center for continuing studies of the technologies and the interface standards that are required for the automated production of small batches of machined parts. The facility will also function as an important technology transfer vehicle for communicating state-of-the-art technology to other government agencies and their contractors.

In the process of developing the AMRF, staff scientists at NBS are delineating and defining those technologies necessary for the automated discrete parts manufacturing systems of the future. Ongoing projects are investigating the application of control theory to manufacturing systems, the mapping and software correction of systematic errors in numerically controlled (NC) machine tools, precision sensors, production process planning, robot control and gripper design, computer vision, machined part deburring, deterministic metrology, and interfaces necessary for overall systems integration. Industrial research associates and university engineers are participating in the work on site. Support for segments of the AMRF is being provided by industry and other government agencies.

A primary objective of the AMRF project is to identify potential standards for the many interfaces that will be required between components of a computer-integrated manufacturing (CIM) system, namely the subsystems which provide for the design of parts and tooling, production process planning, and control of the manufacturing operations. In a typical manufacturing facility, these functions will be performed in computer-aided design (CAD), computer-aided process planning (CAPP), and computer-aided manufacturing (CAM) systems. There are many interfaces in such a facility. For example, the CAD system must provide part design data in usable formats for the CAPP system and for a variety of systems with automated controllers, including industrial robots, NC machine tools, and coordinate measuring machines (CMM). Wherever there are a pair of computerized components interacting, an interface exists. If the components are made by different manufacturers they often cannot be directly coupled except by the development of custom-made interfaces. Building these interfaces one at a time is costly and usually requires a highly skilled staff. Thus, these system integration efforts are normally not within the capabilities of the small and medium-sized machine shops. The solution to this problem is to eliminate the need for custom-made interfaces by the development of industry-wide standards. Such standards will require an agreement among many corporations; no single firm can eliminate this barrier which hinders the development of multi-vendor CIM systems.

II. AMRF Description

To provide a realistic test of potential standard control system architectures and NBS concepts of process or deterministic metrology, an Automated Manufacturing Research Facility (AMRF) is being constructed in a 5000 square foot area of our on-site Instrument Shop (Fig. 1) in Gaithersburg, Maryland.

The AMRF will superficially resemble a flexible manufacturing system (FMS) designed to handle the bulk of the part mix now processed in the NBS Instrument Shop for internal use by scientific staff. This part mix has been studied using group technology (GT) concepts and is similar to that found in a typical machined-parts job shop. The parts produced by the AMRF will be subject to the following constraints which represent the Instrument Shop's work load:

Weight: less than 45 kilograms (100 lbs.)

Size, Prismatic: 300 mm cubes (12" x 12" x 12")

Size, Rotational: 250 mm diameter x 250 mm length (10" x 10")

Parts Run: 1 to 1,000 pieces

Complexity: Up to 4 axes-prismatic

Materials: Steel, stainless steel, aluminum, brass, iron, lucite

The AMRF will address only the manufacture of discrete parts by chip forming metal removal. Hence, the unit operations will include fixturing, milling, drilling, reaming, tapping, boring, turning, facing, threading, cleaning, deburring, and inspection. Currently there are no plans to investigate such processes as automated assembly, welding, hardening, and finishing.

The shop floor layout of the AMRF is based on the concept of fully automated workstations, each with a well-defined set of functions and capable of running in a stand-alone mode. A typical machining workstation will include an industrial robot, an NC machine tool, a local storage buffer for tools and materials, a material handling system interface, and a workstation control computer which integrates and coordinates the operations of the components listed.

The current development plan for the NBS research facility calls for seven stations of varying degrees of complexity. These stations and their component systems are representative of general purpose production equipment in common use throughout the United States. The equipment selected also meets the machining needs of the NBS Instrument Shops as indicated by the group technology study. The seven stations are:

(a) Horizontal Machining Station

(b) Vertical Machining Station

(c) Turning Station

(d) Inspection Station

(e) Materials Inventory Station

(f) Materials Handling System

(g) Housekeeping System

Items (f) and (g), the Material Handling and the Housekeeping Systems, are not strictly stations since they are non-localized in the facility. From the point of view of the control system, however, they will be treated as stations.

The control architecture under investigation is shown in (Fig. 2). The two distributed hierarchical data bases contain all facility planning and control information.

The planning data base consists of all data necessary to manufacture the selected part mix, including part dimensions and geometry, desired grip points for robot handling, and tool and material requirements. The process plans for routing and scheduling, as well as cutter location files needed to perform the various machining operations are found in the same data base.

The control data base contains dynamic, factory status information, including management information data used to track order processing. Also included are the status data for all control systems, tools, robots, and computers in the hierarchy, as well as each work order in progress. Both data bases are accessed by a number of control modules in the hierarchy.

Information is passed from one control level to another and from one computing module to another through the data bases which serve as common memory. The control system of the AMRF is based on a hierarchy of task decomposition modules and feedback processors. Higher level control modules decompose complex tasks into simpler ones. The simple tasks are issued as commands to controllers at the next lower level. Feedback processors scan the appropriate levels of the data base, and extract and process sensory and status information needed by control modules at higher levels. This processed sensory feedback data is also passed between control systems through the common memory mechanism. The control and data management architecture clearly distinguishes the AMRF from "just another FMS" and provides the basis for much of the NBS research activities.

The paper describes research projects underway to implement the AMRF with emphasis placed on a major aspect of the project, the development of the manufacturing planning and control software. Also described are the support software tools used in the development of the control system. Finally the system hardware integration projects, including the enhancement of commercially available hardware, such as robots and machine tools, with special sensors and controllers to provide compatibility with NBS control and interface concepts, are described.

III. Manufacturing Planning and Control Software

The purpose of this portion of the project is to develop an understanding of the software modules that will comprise future computer integrated manufacturing systems. To accomplish this, the NBS approach has been to use structured software development techniques to analyze the functional requirements of systems, develop an overall software systems architecture, and decompose this architecture into designs for component modules. Particular attention has been placed upon the data that must be communicated between modules, and the representation of information within the system and to the user. These data structures will provide a foundation for the development of potential standard interfaces.

The software systems are being developed on the AMRF Research Computer Facility which consists of a large minicomputer with 4 Mbytes of main memory, 1200 Mbytes of disk storage, 40 terminal ports, magnetic tape drive, and printer. There are a number of general programming languages, data base management systems, and graphical support systems available. In addition, there are several graphics devices which provide both vector and raster displays for the development of user interfaces and manufacturing simulations.

The manufacturing planning and control software research activities are described in terms of four major efforts: Production Control, Distributed Automated Process Planning, Database Systems, and Network Communications.

Production Control

The objective of this research is to develop: (1) a real-time, adaptive, state-table driven, hierarchical production control system for the AMRF that provides the flexibility and adaptive behavior of existing manual control systems, and (2) specifications of potential standard interfaces for modular, multi-vendor integrated manufacturing control systems.

There are a number of important control concepts that have served as a foundation for the development of the AMRF control architecture. As these concepts have had a major impact on many portions of the project, they are presented in some detail for background:

(a) Hierarchical control. This organization is equivalent to the line or tree structure found in many conventional manufacturing systems. Each system takes commands from only one higher level system, but may direct several others at the next lower level. Long range goals or tasks enter the system at the highest level and are decomposed into sequences of subtasks to be executed as procedures at that level, or output as commands to the next lower level.

(b) Local intelligence. At each level in the control hierarchy this capability enables the system to decompose tasks, analyze feedback, and respond to problems at that level. It also ensures that only major tasks, those having a global impact, will be handled by the decision making systems at the higher control levels.

(c) State machines. To ensure that the control system is deterministic, it will be defined as a network of state machines. All inputs, outputs states, and state transitions of a control system are identified in a state graph. The state graph is used to develop a state table that will be processed as described below.

(d) Control cycle. A time interval, called a control cycle, is defined for each control subsystem; this cycle determines how often its state table is processed. The processing of a state table is accomplished by sampling state variables, searching the table for a state that matches the sampled variables, executing the routines associated with the state identified, and generating the outputs. The cycle at each level must be short enough to maintain system stability. The processor must be able to identify the current state and generate appropriate outputs before the behavior of the system deviates beyond acceptable ranges.

(e) Planning horizon. The amount of time any system plans into the future to perform the tasks at its control level is defined as its planning horizon. This horizon is determined by the nature of the tasks or goals that are passed down as commands from the next higher level. Systems do not know about events or activities which will occur beyond their planning horizon. In general, a system cannot plan beyond its current command or goal for it does not know what the next command may be. By defining shorter and shorter planning horizons at each successively lower control level, the processing capacity required for planning during a control cycle is kept to a minimum at every level.

(f) Hierarchical scheduling. This technique, the partitioning of activities or jobs by large time increments at the higher levels and smaller increments at the lower levels, enables each control system to make the decisions that are necessary at its level for efficient operation within the bounds established by higher levels. For example, a high level control system may schedule by grouping jobs into partitions or packets by the month that the job is to be performed. The jobs in packet #1, are accomplished in the first month; packet #2, the next month, etc. The next lower control level is only tasked with the jobs in packet #1, thus limiting its planning horizon to the current month. It divides the jobs into packets by weeks, into packet #1.1, packet #1.2, etc. The next lower level, with one week planning horizon, would be tasked with packet #1.1.

Since the hierarchical control structure requires that commands must flow downward, lower level systems cannot by themselves move a job out of the packet given to them by a higher level. If the job cannot be processed in the specified time frame, the reason for the failure must be reported as feedback to the next higher level. The controlling system at the next level may then take action to either circumvent the failure or reschedule the job by tasking the subordinate system with a modified packet of jobs.

(g) Communication by common memory. All systems will communicate by passing messages through mailboxes in common memory or a shared data base. Each system has command and feedback mailboxes where its controlling system can write commands and where controlled systems and sensors can provide feedback. Each mailbox can be written to by only one system, but can be read by any other system. The mailboxes, updated every control cycle as a part of the state machine implementation, also provide a snapshot of the current state of the system that is useful both for diagnostic analyses and system restarts.

A general-purpose, decision table-based control system is being developed that is intended to be transportable and implementable at any level in the AMRF. The system will be modular and programmed in high-level languages, such as LISP, C, PASCAL, and ADA, to facilitate its operation on a variety of different processors. The decision or state table program format will be used to ensure the speed and reliability that is required of a real-time control system. All communications between table processors at different control levels within the system will be performed through transactions in the common data base. Major modules of the state table development system will include special software for handling the table structures including an editor, a compiler, a data management system interface, a table execution processor and a testing/debugging system. Components of this system have been implemented and are currently in use.

The hierarchical system will process the state tables in real-time to provide for adaptive production control at each level. The table processors will be integrated into the Production Control System (PCS), a hierarchy of five major levels. The levels are (in descending order): Facility, Shop, Cell, Workstation, and Equipment. Functions performed at the Facility level include manufacturing engineering (design, process planning, production planning), information management (order handling, cost accounting, inventory management, procurement, and performance monitoring), and long-range scheduling. Shop level functions include shorter-range production scheduling, resource allocation, production task management, and support activities management. Cell level functions include production job analysis, reporting, routing, scheduling, and workstation monitoring. Support activities include a variety of functions such as material storage, transportation, tool assembly, cleaning and deburring. Workstation level control includes the supervision and coordination of base machining, handling, and measurement operations. A Production Control Language (PCL) is under development which will permit the programming of each control level in a user-oriented language which reflects the terminology and activities of non-automated job shop management systems.

At the cell control level, the concept of the group technology manufacturing cell is being extended by the development of software-based production management systems (virtual cells). The virtual cell configuration varies dynamically according to the processing resource requirements of a batch during the production process. These virtual cells will be responsible for managing the production of non-identical parts that have been batched by using a group technology classification scheme. The virtual cell will exist solely as a control process that exists for the duration of the production run of the batch. This approach represents a considerable change in the philosophy of cell control. In the past cells have had static control structures that were normally associated with a fixed physical grouping of machinery. The cell controller will maintain a PERT-type network to track progress and predict when it will need to request the assignment of specific workstations from the shop controller in order to process its batch of parts. Workstations will be allocated to cells by the shop level resource allocator only when they are requested because of need. Idle workstations will be assigned to a workstation pool cell controller. This structure promises to provide much of the flexibility found in manual job shops while increasing efficiency through automation.

<u>Distributed Automated Process Planning</u>

The objective of this recently initiated subproject is to (1) identify and provide the process planning functions that must be performed in a totally automated facility, and (2) investigate artificial intelligence and expert system techniques for distributing planning functions within the AMRF. Local intelligence will be developed for each control module. Standard techniques will be developed to allow modules at different levels in the hierarchy to access the planning capabilities and knowledge bases of other modules, as necessary to perform distributed planning.

In an automated facility process plans must be comprehensive in that they must specify all the details of how to produce a part; including selection of materials, machine tools, robot grippers, grip points, fixtures, clamping points, inspection procedures, cutter paths and parameters, coolants, and any special material transportation considerations. The development of the AMRF process planning system will be accomplished through four development stages: interactive tools, variant system, generative system, and finally, a distributed system.

(a) <u>Interactive tools</u> - User interfaces will be developed to allow planners to more efficiently use existing software to interactively develop process control programs and data. A user-oriented language for process planning will be developed to plan for the AMRF workstations the part processing, inspection, and handling. The interactive tools package will assist the planner in: 1) the transfer of CAD data files to process planning, 2) the selection of process planning parameters, and 3) the transfer of the planning and control data to part processing and material handling workstations.

(b) Variant system - This system will be used to develop production plans using variant techniques (i.e. retrieval and editing of existing plans board on a GT code) for selected AMRF part families. Existing variant systems will be integrated into the AMRF and used wherever possible. Some of the functions performed manually in the interactive tools stage will be automated.

(c) Generative system - This next stage will incorporate solid modelling, geometric reasoning, and expert system software to generate process plans from CAD data and models of system process capabilities.

(d) Distributed system - In this final stage of development the planning logic and its associated software, previously developed for centralized planning, is decomposed and integrated into the appropriate control modules throughout the facility. This distribution will provide local intelligent planning in each control system. Each system, whether it be a shop, cell, workstation, or equipment controller, will be able to operate in a stand-alone mode and plan processes that are within the capabilities of its resources.

The distributed process planning system of the AMRF will consist of a hierarchical network of planning systems that reflect the control tasks at each level. Systems will have their own particular planning specialties. Consulting relationships between systems, similar to those found between different levels of managers and operators in conventional systems, will be used to obtain answers which fall outside of any system's domain of expertise. This distributed approach should allow for real-time modification of process plans at the appropriate control level and ensure efficient usage of system capabilities as the systems dynamically change with time. This project will make heavy use of the expert system technology discussed in Section 4.

Database Systems

The objective of the AMRF data base work is to (1) utilize data base management techniques to develop flexible data-driven control systems which provide the information required by the AMRF operating in a distributed and real-time control processing environment, and (2) define and develop the data structures necessary to support an automated manufacturing system.

The first subproject is the identification of the data structures which will be required to support the AMRF. An analysis of data requirements is being made for each function and level of control within the AMRF. This includes the data requirements of a typical manufacturing operation, those of an automated facility, and those specific to the research needs of the AMRF. The first prototype database system will operate in an interactive but stand-alone fashion utilizing menu-driven interfaces. The next stage will be aimed at fine tuning database structures, developing the interface specifications between systems and levels of control, generating a workable distribution of the data, and identifying data which for performance reasons must be replicated in low level processors. Data dictionary functions will be heavily employed during the design and implementation phases. An automated data dictionary can be used to control standards, facilitate shared access to data, and allow for distributed systems.

The second database effort is concerned with the development of the software architecture to maintain this data and permit access to it. The database software must support a distributed processing environment. At lower levels of control, namely at workstations and equipment, processes will run on special purpose microcomputer-based systems, and rapid response times are imperative. Commercial data base systems, in particular those that can be extended by higher level programming languages, will be used at higher levels, but may not be suitable at lower levels.

A common data definition language and a common data manipulation language will be defined for interfacing to the control systems that access it. The databases will be organized into a logical view that provides a data model that describes how each data element is used within the AMRF. This logical view allows the control process, to access only the information that is relevant to a particular functional task. This logical access to data makes the actual physical organization of data transparent, and permits it to be shared by multiple users.

Network Communication

The objective of this network communication project is to provide a communication link that allows all system developers to interface their terminals to any AMRF computer or control process, and to provide network and local communications mechanisms for control processes within the AMRF.

The network is being implemented using commercially available hardware. Standard network interfaces will be obtained to handle the variety of computers to be linked via the network. The heart of the research effort is the development of the software interface standards that will provide AMRF processes with a means for communicating with (1) each other, (2) the operating systems of control computers, (3) the local communications system interface, the distributed data management system, and (4) the user display devices.

A common communications language will provide a standard method for naming, opening, reading, writing, and closing logical communication channels, i.e. mailboxes. A process management command language would provide common terminology and syntax for naming, creating, moving, suspending, interconnecting, setting priorities, and performing other computer process management functions.

Communications nodes will be associated with one or more processors which share a common physical interface to the network. The computing systems of the node will support functions such as: manufacturing control, data administration, program and communication control. Processes within a node access each other by reference to logical names, their associated standard interchange mailboxes, and the common local data path.

IV. Software Development Environments

In order to effectively develop the manufacturing application software described in the last section, it is imperative to provide a suitable environment for software development. In addition to the standard set of software tools that are normally used in a software project, special emphasis is being given to four projects: (1) the development of user-oriented graphics interfaces, (2) system design, development, and testing through simulation and emulation techniques, (3) the use of computer-aided-design (CAD) data to direct planning and control systems for quality assurance, and (4) the application of the artificial intelligent and expert system technology to these systems.

Manufacturing Graphics Interfaces

The objective of the graphics project is to develop a system for image input, generation, output, and storage that satisfies the needs of control operators and users of automated manufacturing systems. Graphics capabilities must be provided for control system interfaces, data entry, computer-aided design, statistical analysis, process planning, and process simulation.

A graphics interface system is being developed to allow processes to communicate with any suitable graphics device through the common data base of the AMRF. Commercial and research graphics packages are being obtained and tailored to meet the immediate needs of the AMRF. Libraries of graphics tools for the display of manufacturing entities are being assembled to enable the simulation of manufacturing systems. These tools will provide a capability for defining two and three dimensional graphical pictures, shading, texturing, hidden-line removal, translation, rotation, scaling, windowing, clipping, grouping of graphic entities, key-frame animation, etc. Dynamic graphics icons or symbols are being developed which will display facility status and permit the AMRF operators and staff to interact with the control system via graphics displays that are pictorially representative of the manufacturing system.

Control System Emulation

The objective of the control system emulation project is to develop the models and implement the software needed to simulate/ emulate the AMRF in order to test system software and concepts before final development and integration of modules into the control hierarchy.

The AMRF is being modeled using emulation, a special form of simulation in which the rules governing the operation of a planned system are duplicated and the user interacts with the emulated system as if it were the real one. This technique is being employed to emulate the operation of the modular hierarchical control software of the AMRF while operation of the shop floor equipment is being simulated or approximated through timing estimates correlated to movement through a given distance, etc. The primary advantage of emulation, as compared to conventional simulation, is that it serves as a prototype for parts of the real system, and those parts may be developed before the actual hardware is available.

The AMRF emulation is a collection of computer programs written primarily in PRAXIS, a language similar to ADA, developed by Bolt, Beranek, and Newman. The emulation follows the structure of the AMRF modular hierarchical feedback control system. The modules of the AMRF emulation structure are state machines that interact through a shared memory where the passing of control status information is synchronized to occur at specified time intervals. Communication and computing delays are emulated, along with the allocation of modules to different physical processors. The whole of the AMRF is to be emulated with each module (e.g., workstation), on each level, distinctly isolated as a separate process in order to facilitate its replacement with actual control hardware and software. The data base structures of the emulation approximate those anticipated for the AMRF.

The emulator is being used as a design aid in the development of system software. Designers can test out their ideas before implementing the code in its final form. By this technique it is possible to maintain an up-to-date description of the design of all control levels in the AMRF. At the present time, the cell control level of the AMRF is being modeled to test the virtual cell concept.

CAD-Directed Inspection

The objectives of the CAD-directed inspection project are to (1) research and develop methods for using CAD data bases to direct inspection systems in the efficient and accurate measurement of dimensional properties of a workpiece; and (2) investigate methods for automatically generating programs from CAD data bases for optical and mechanical inspection systems, robot vision systems, and robot control systems.

The initial work is being done with a 3-D mechanical coordinate measuring machine (CMM) using touch-trigger probes. Work will be extended later to include other sensing technologies, such as continuous tracing (using proportional probes), optical sensing, and machine vision. Regardless of the technology used for measurement, the main thrust of the project will be toward a fully automated inspection system which derives and executes testing strategies directly from part design data.

An important part of this project is the development of inspection languages which will allow inspection procedures by using CAD data. A programming system will be developed so that a user can input inspection requirements through a CAD workstation, using the geometric data available for the part. A translator will reference to the CAD data to convert inspection language programs into commands that the CMM can execute.

The current hierarchical control system design for the inspection system actually requires two languages. One language is that which is used by a programmer to specify an inspection procedure. This language will be primarily a graphical language in which the programmer identifies inspection actions and part features from which data to drive the inspection will be derived. Thus, the programmer may specify that the true position tolerance of a hole pattern be verified, and will "point" to a graphic display of the part to identify the feature of interest. From that information, the programming system will either be able to automatically generate the appropriate lower-level actions and invoke the appropriate sensory processing algorithms, or will prompt the programmer for a more detailed breakdown of the task.

The second language referred to above consists of the various commands used to communicate between the different levels of the control system itself. In many ways, this language will be similar to the language used by an inspection programmer, since defining a task decomposition is by-and-large a specification of a sequence of lower-level goals to be accomplished. These lower-level goals form the commands communicated between levels of the control system during execution.

Later versions of the system will use inspection goals that are entered into the CAD data base through the part design system. These goals will be used in the automatic generation of inspection procedures expressed in the inspection language previously discussed. A program generation system will be implemented using heuristic techniques of problem-reduction and state-space search to develop the sequences of actions required to satisfy each inspection goal. The program generator will also identify the inspection station control requirements, such as part fixturing and probe changing, necessary for execution of the inspection program. The system is being developed using such tools as geometric modeling, emulation, and expert systems.

In addition it is necessary to make extensions to CAD systems in order that they may acquire new data which will allow for (1) specifying part designs in ways that reflect the constraints and interactions among part dimensions and other parameters of designs, (2) representing non-geometric data related to part designs, and (3) defining procedures for interaction between CAD and other systems of the automated facility.

The architecture for the CAD-Directed Inspection control system is very similar to the hierarchical control architecture used in robot control and in the AMRF. These systems consist of multiple state machine modules communicating through a common memory. Programs for these systems consist of state table and data structure definitions for the modules in the hierarchy.

The hierarchical control system emulator, developed for the AMRF, is being used as a design tool for CAD-directed inspection. Its use has involved integrating the emulator with the geometric modeling and graphics functions of PADL-2, with the coordinate measuring machine and other equipment to be used in the project, and with a program development environment including an editor, a data dictionary, and documentation aids.

Expert Systems

The objective of the expert systems project is to apply knowledge-based system technology to build extensible expert systems for manufacturing planning and control.

Artificial intelligence techniques, more specifically, the technology of knowledge-based, problem-solving or expert systems, have application in several areas of the AMRF. Knowledge-based systems are appropriate problem-solving tools in domains where (1) there exists no unifying, concise theory describing the problem domain, (2) knowledge (facts, beliefs, and heuristics) is acquired in small increments (production rules), and (3) the utility of a piece of knowledge cannot always be determined in advance (i.e., fixed sequences of computation are inappropriate).

The expert system technology will first be directed towards CAD-directed inspection and production process planning. In the current version of the system, there are three activities where expert systems will be needed. One is in planning, including searching for collision-free paths, planning a measurement strategy, and optimization. Another immediate application is pattern recognition; where sensory data from the measurement must be classified and compared to the stored part descriptions. The third area is simulation, where rules describing the behavior of the physical measurement system will be used as part of the simulation of the inspection control system.

The major steps in building these expert systems are to develop a problem-solving architecture, build and organize a knowledge base of rules, and integrate this computational capability into the overall system.

V. System Hardware Integration

At the lowest level of the manufacturing control hierarchy is the elemental control unit represented by robots, machine tools, carts, etc. Projects at this level address the problem of making the unit more responsive to a changing environment by incorporating sensory feedback adaptive control for improved accuracy and performance.

Research is being performed in the following areas: (a) work station control systems, (b) machine tool metrology, (c) machine tool sensors, (d) real-time robotic control systems, (e) robot vision, and (f) non-visual robot sensors.

Workstation Control System

The workstation control system project involves the integration of automated manufacturing equipment into production work stations for small lot manufacturing. The work involves extending and enhancing numerically controlled machine tools and industrial robot manipulators to form flexible, coordinated, and sensory interactive systems. Research is focused on the generation and verification of control data, the development of real-time software for synchronization and control, and the development of interface standards and technical guidelines.

The first workstation consists of a horizontal machining center that has been integrated under work station control with a robot, a robot cart, and two loading platforms, and a simple fixturing system.

The coordination and supervision of these equipments is the responsibility of the workstation controller. Essential features of the workstation controller are: unattended operation of the workstation, extensive use of sensors, ability of the program to account for changing machine availability, varying part designs and batch sizes, and status reporting to higher control levels.

The workstation receives raw materials, modular fixturing components, and robot and NC tooling from inventory; machines batches of parts, and releases all materials to inventory. Coordination of these operations within the workstation is centralized in the workstation controller. As a level in the hierarchical control system of the AMRF, the work station controller receives production commands from the cell controller, decomposes these commands, issues commands to manufacturing equipment controllers to coordinate manufacturing operations and reports work station status back to the cell controller once each control cycle.

Machine Tool Metrology

Machine tool metrology research is concerned with the improvement of measurement and machining accuracy in existing hardware through the application of dimensional traceability (or deterministic metrology). Some specific efforts include (a) improvement of the point-to-point positioning accuracy of a CNC machining center through the use of on-line computer modeling and process monitoring and (b) development of quantitive techniques for evaluating and improving the performance of coordinate measuring machines.

The machining accuracy enhancement is being performed with a vertical spindle CNC Machining Center, using a Dual Minicomputer system and Laser Interferometer system. The enhanced machine tool will be used to produce a pair of high precision, high speed, rotary postage stamp perforating cylinders for the Bureau of Engraving and Printing. The successful manufacturing of these cylinders requires a positioning accuracy of ±2 micrometer over a one meter length for the drilling of approximately 50,000 holes (1 mm diameter) in the pair of cylinders.

Several aspects of machining accuracy enhancements are utilized (1) static positioning errors: corrections from calibration data are supplied from the computer into the servo loop of the machining center (2) thermal errors: data from an array of thermal sensors are used for quasi-real time position correction,. (3) dynamic errors: tool wear, tool chatter, spindle run-out and machine vibration are taken into account, and (4) table deformation and loading: theoretical prediction and experimental verification of the natural frequencies and mode shapes of machine tools.

In coordinate measuring machine (CMM) research, a complete set of kinematic errors for a computer controlled CMM have been measured and incorporated into error modeling software on a desktop computer. This model, combined with differential thermal expansion calculations, has been able to predict linear positioning errors within four micrometers for an arbitrary, body diagonal of the machine. The testing of 3-D ball plates continues as part of our effort to support the development of standard acceptance tests for CMMs.

Machine Tool Sensor Systems

With the advent of fully automated functions, on-line tool sensing is more important than ever before since operators are not normally present to monitor the process.

One research effort has resulted in the development of Drill-Up, an instrument which was originally designed to avoid breakage of small-diameter drills used on automatic-feed drilling machines with a spindle-retract capability. The instrument determines that breakage is imminent and commands the drilling machine to retract the drill. The input sensor is a piezoelectric accelerometer which is mechanically coupled to the workpiece. Potential drill breakage is determined by time-domain analysis of the accelerometer signal. A calibration routine automatically adjusts to the normal amplitude of the signal. Large amplitude accelerations, synchronous with the drill rotation, have been found to be indicative of improper cutting. Drill-Up's detection method is based on the characteristic deflection of a column with one rigid support on the end opposite an axial load. When the drilling is improper, due to factors such as a worn cutting edge or a hard spot on the workpiece, the material cannot be removed as fast as the drill is being fed into it. When this occurs, the drill deflects as a column and induces a vibration signal as it scrapes on the side or bottom of the hole. If this is allowed to continue, the column will collapse, resulting in drill failure. The detection method recognizes that scraping in the hole is synchronous with the rotation of the spindle.

A second project is concerned with spindle error testing and analysis. Besides the quasi-static errors of imperfect geometry, load deformations and thermal deformations, a machine tool has errors associated with its dynamic behavior. The most important of these errors are the spindle error motions and the kinematic errors associated with the coordination of axis motion and vibrations, both self-induced and forced.

A microprocessor-based system has been developed for spindle error testing and design that uses a position encoder, a high-speed sample-and-hold circuit, and an analog-to-digital converter. In addition, a displacement transducer with wide-bandwidth and extended dynamic range has been developed such that 512 points may be analyzed at rotational speeds up to 10,000 rpm. Because of the low cost of microprocessors, this system can be dedicated to a machining center for continuous monitoring.

Robotic Real Time Control System

The robotic real-time control system program addresses three major areas - definition of a robot systems architecture in order to accomplish real-time control, specification of functional module interfaces, and the study of user interfaces for programming and diagnostics. The system architecture is a partitioning the system into component functional modules. Interfaces between these modules can be described as well-defined input and output data buffers. These data buffers, which reside in a common memory, become the mechanisms for interfacing between modules and therefore for interfacing between the control system and sensors, robots, supervisory control, etc. When a user is to interact with a system of this complexity, additional functional modules are required. Their interfaces should be through the same type of data buffers described above and thus allow the use of various programming and display modules.

A sensory-interactive robot control system has been developed and implemented on two robots: a Stanford Arm and a PUMA 450. It illustrates the following points:

(a) generic task decomposition control modules operating as independent state machines in a hierarchical multi-level system.

(b) a common-memory communications architecture, for a modularly structured system, implemented on single or multiple processors.

(c) common-memory resident data interfaces between the modules of a structured system, to be used as the mechanism for interfacing other sensors, supervisory control, data bases, and different robot hardware.

(d) table-structured mechanisms (such as state-tables) for the representation of data and program control in a convenient form for user interaction and modification.

(e) the use of diagnostic tools to access the variables in common memory to provide real-time trace of user defined variables and their subsequent formatted display.

<u>Robot Vision System</u>

The robot vision work is being performed in three major research areas: 1) the integration of robot control theory with image processing systems, 2) real-time gray scale vision processing, and 3) fast acquistion of range data.

The application of control theory to image processing systems was undertaken to support the AMRF robot vision needs. It capitalizes on the fact that robots encounter sets of images which form continuous sequences. A system is in development which serves as a hierarchically organized internal model of the sensory world by continually testing the model's predictions and correcting the model. The current state of the model is continuously available to the control system. At present this project is being implemented using geometric and topological models derived from CAD descriptions, and using the 6-D structured light vision system to test the predictions.

In support of the longer term AMRF requirements, and to provide a facility for vision competency research, a multi-stage gray-scale image processing pipeline is being designed and constructed. It will analyze a continuous stream of consecutive 256 x 256, eight-bit images, through a series of stages, at frame rate. A variety of arithmetic and Boolean neighborhood operators may be applied to each pixel at each stage, and multiple feedback loops exist between stages. A unique architecture allows processing within the device to be guided by data on expected models from above as well as data from below. Ultimately, this device will be used in conjunction with the AMRF robot vision system described above.

As part of the vision research, experiments are being conducted using multiple structured light frames in the acquisition of full-frame range images. The NBS system will use eight frames of structured light, and is capable of analyzing a 256 x 256 image of eight-bit ranges at frame rate. Thus, a full-frame eight-bit range image can be acquired in about 0.3 seconds. This device will find application both in robot vision and in inspection tasks.

The ability of the "6-D" robot vision system to acquire unknown three-dimensional objects, arbitrarily positioned in 3-space has been demonstrated. It can then guide the robot in useful interaction with the objects. An object unknown to the robot's software can be placed in a random location with a random 3-D orientation. Using flood flashes, the robot can discover the object. Alternating flood flashes with two-plane flashes, it approaches the object and discovers the 3-D orientation of its largest surface. The robot then positions itself normal to that surface. Using the combined information from both illumination types, it correctly interprets the object's 2-D outline in 3-space and locates its centroid and principal axis. It then attempts to grasp it squarely across its narrowest dimension at the center of gravity and remove it from the field. Because it can directly sense the range to surfaces, it can correctly repeat this process to unload a stack of objects. Because it is not interpreting the scene with respect to internal models of objects or the physics of grasping, correct performance is currently limited to simple situations.

<u>Robot Sensor Systems</u>

Robot sensor systems are being developed through a number of interrelated projects:

(a) AMRF Robot Integration - Each commercial robot in the AMRF will be equipped with an NBS Controller, a sensory system, an instumented end-effector (gripper) and a safety system. This project is the integration and test of all of the above systems with each commercial robot.

(b) Instrumented Gripper - Each work station in the AMRF may require different types of grippers. The current development effort is a two-fingered pneumatically actuated gripper which can be servoed on finger position and gripping force. This gripper will be used on the horizontal machining center robot.

(c) Safety Systems - Currently under development is a "Watchdog" Safety Computer which will monitor robot joint velocity, acceleration, and position. The computer will have independent capability to stop the robot if it exceeds pre-set limits.

(d) Robot Cart - A commercial robot cart is being modified for control with an on-board microprocessor and a command and status R/F communications link.

(e) Robot Performance Measurement - This project will develop techniques which can be standardized to achieve automated on-site measurement, analysis, evaluation and control of robot performance.

VI. Conclusion

This paper has described the research efforts at the National Bureau of Standards to construct an Automated Manufacturing Research Facility to improved capability to measure in-process operations, and the develop specifications for potential interface standards for the various elements of automated manufacturing facilities.

VII. Acknowledgment.

This paper has been prepared to summarize the preliminary results and integrated reports by many NBS staff and AMRF project team members, too numerous to list and properly credit here.

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VIII. References

[1] Simpson, J. S., Hocken, R. J., and Albus, J. S., The Automated Manufacturing Research Facility of the National Bureau of Standards, Journal of Manufacturing Systems, Volume 1, Number 1, 1983.

[2] Albus, J. S., McLean, C. R., Barbera, A. J., and Fitzgerald, M. L., Hierarchical Control for Robots in an Automated Factory. Presented at 13th ISIR/Robot 7 Symposium Chicago, Illinois, April 1983.

[3] Barbera, A. J., Fitzgerald, M. L., and Albus, J. S. Concepts for A Real-Time Sensory-Interactive Control System Architecture. In Proceedings of the Fourteenth Southeastern Symposium on System Theory, April 1982.

[4] Kent, E., Albus, J. S., Mansbach, P., Nashman, M., Palombo, L., Rutkowski, W., Wheatley, T., and Shneier, M., "Robot Sensing for a Hierarchical Control System." Presented at the 13th International Symposium on Industrial Robots/Robots 7, Chicago, IL, April 1983.

[5] Yee, K. W., A guide for the Construction and Operation of Drill-up. NBSIR 82-2590, National Bureau of Standards, October 1982. Available from NTIS. 26 pp.

[6] McLean, C. R., Bloom, H. M. and Hopp, T. H., The Virtual Manufacturing Cell. Fourth IFAC Symposium, Information Control Problems in Manufacturing Technology, October 26-28, 1982.

[7] McLean, C. R., Mitchell, M., and Barkmeyer, A Computer Architecture for Small-batch Manufacturing. IEEE Spectrum, May 1983.

[8] Rippey, W. and Scott, Harry, Real Time Control of a Machining Work Station, NCS, April 1983

[9] Hopp T. H. and Lau, K. C. A Hierarchical, Model-Based, Control System for Inspection. In American Society for Testing and Materials, May 1983.

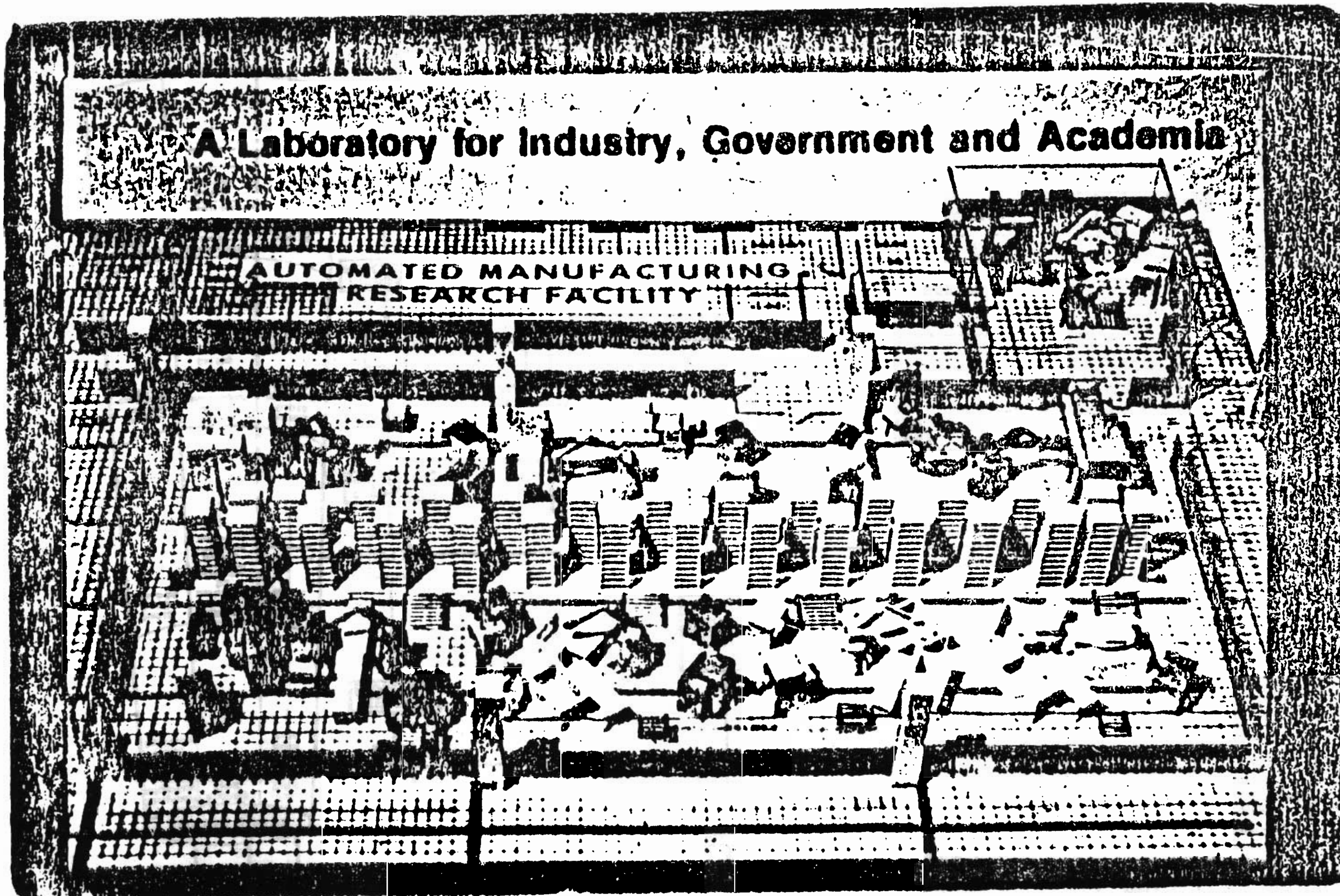

Figure 1: Physical layout of the AMRF.

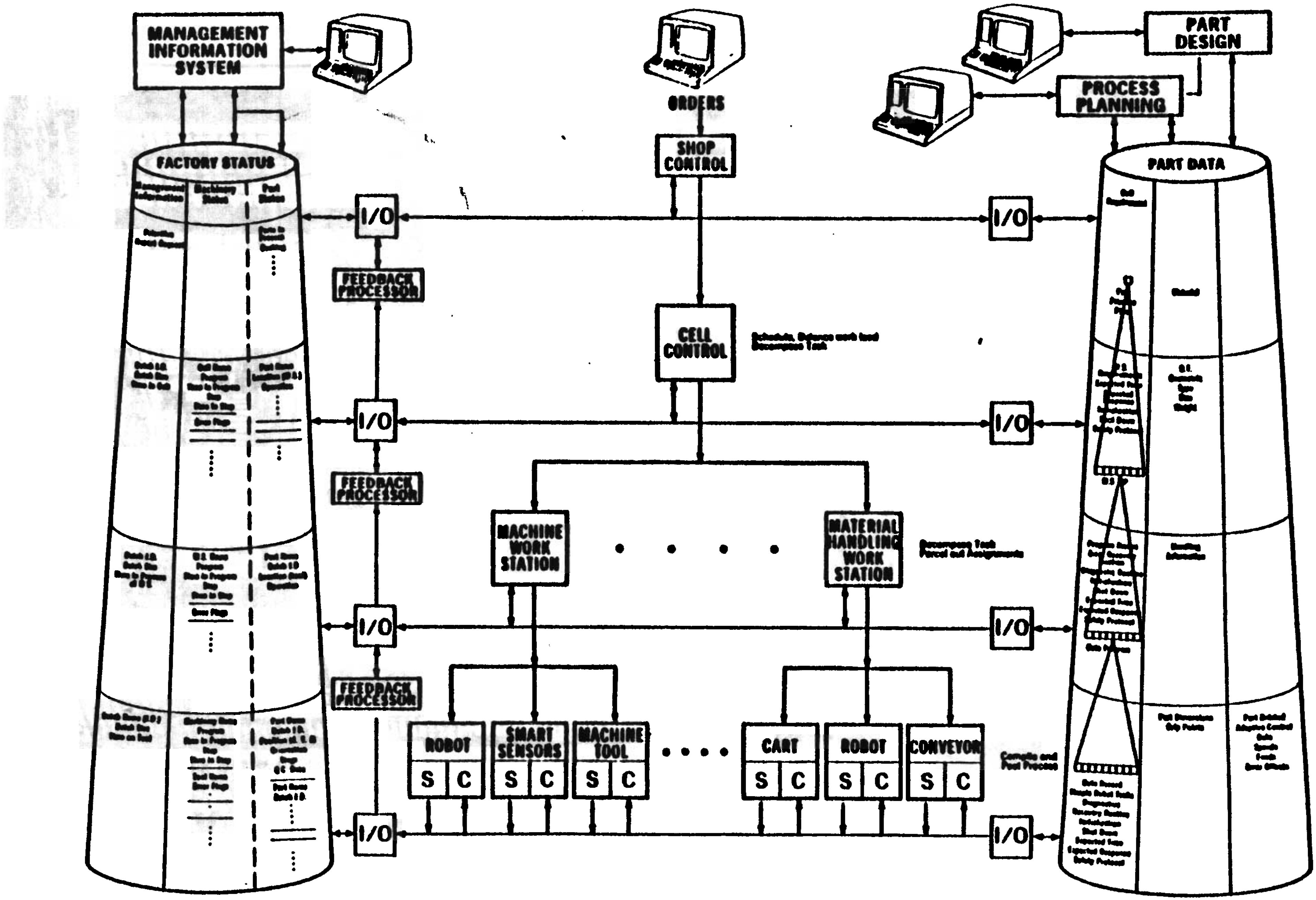

Figure 2. A hierarchical architecture for a factory control system.